Assessing agronomic and environmental implications of different N fertilisation strategies in grain cropping systems on Oxisols.

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Abstract

A multi-season ^{15}N tracer recovery experiment was conducted on an Oxisol cropped with wheat, maize and sorghum to compare crop N recoveries of different fertilisation strategies and determine the main pathways of N losses that limit N recovery in these agroecosystems. In the wheat and maize seasons ^{15}N-labelled fertiliser was applied as conventional urea (CONV) and urea coated with a nitrification inhibitor (DMPP). In sorghum, the fate of ^{15}N-labelled urea was monitored in this crop following a legume ley pasture (L70) or a grass ley pasture (G100). The fertiliser N applied to sorghum in the legume-cereal rotation was reduced (70 kg N ha^{-1}) compared to the grass-cereal (100 kg N ha^{-1}) to assess the availability of the N residual from the legume ley pasture. Average crop N recoveries were 73% (CONV) and 77% (DMPP) in wheat and 50% (CONV) and 51% (DMPP) in maize, while in sorghum were 71% (L70) and 53% (G100). Data gathered in this study indicate that the intrinsic physical and chemical conditions of Oxisols can be extremely effective in limiting N losses via deep leaching or denitrification. Elevated crop ^{15}N recoveries can be therefore obtained in subtropical Oxisols using conventional urea while in these agroecosystems DMPP urea has no significant scope to increase fertiliser N recovery in the crop. Overall, introducing a legume phase to limit the fertiliser N requirements of the following cereal crop proved to be the most effective strategy to reduce N losses and increase fertiliser N recovery.

Keywords: Oxisols; nitrogen recovery; NUE; DMPP; nitrification inhibitor; cereals; legumes; wheat; maize; sorghum; subtropical

Abbreviations: DM: Dry matter; Ndff: N derived from labelled fertiliser.

Introduction

Half the world's population live in regions dominated by acid soils (Yang et al. 2004), 18.4 % of which are classified as Oxisols (von Uexküll and Mutert 1995). Oxisols are the most common soil type in the tropics and subtropics, representing approximately 46% and 23% of soil area in these regions, respectively (Buol and Eswaran 1999), and are mainly located in South America, Africa and Asia (von Uexküll and Mutert 1995).

More susceptible to degradation than most soils and characterised by low natural fertility, Oxisols had been relegated to marginal agricultural practices until the Green Revolution (Borlaug and Dowswell 1997; Thomas and Ayarza 1999). However, with modern technologies many of the constraints of Oxisols can be amended and these soils are now regarded as the most extensive agricultural frontier in the world. Today, Oxisols are capable of high productivity levels and support sufficient food production and economic returns to feed millions of peoples, particularly in tropical and subtropical regions (Fageria and Baligar 2008). For example in Brazil, the country with the greatest extent of arable Oxisols in the world, the area of Oxisols cultivated with grain crops increased from 10 million ha in 1970 to 48 million ha in 2011 (Scheid Lopes et al. 2012; Thomas and Ayarza 1999) and alone contributes to 4.3% of the world's current grain production (FAOSTAT 2013; Fischer 2009).

However, there is growing concern about the environmental and agronomic implications of intensive cropping of Oxisols. Nearly all future demographic growth is projected to take place in tropical and subtropical countries (UNFPA 2011), meaning a greater pressure on Oxisols to meet future grain demand (Fageria and Baligar 2008). There will be economic and environmental pressures for any increase in grain production to occur without intensification of synthetic N fertiliser use, as the manufacture and use of these products has major implications in terms of water quality, energy consumption and greenhouse emissions (Crews and Peoples 2004; Jensen et al. 2012; Müller and Gattinger 2013). There is therefore an urgent need to develop N management strategies and farming systems that can reduce the need for synthetic N fertiliser in Oxisols and improve fertiliser N recovery in grain cropping systems.

Under certain conditions, the application of nitrification inhibitors to urea-based fertilisers has been shown to improve yields through an increased crop N recovery (Kawakami et al. 2012; Linzmeier et al. 2001; Pasda et al. 2001). However, the efficiency of nitrification inhibitors is highly dependent on soil and climatic conditions and their use substantially increases fertilisation costs (Eagle et al. 2012). Alternatively, many authors have proposed the reintroduction of legumes in grain-based cropping systems as one possible strategy to reduce synthetic N inputs whilst sustaining crop yields (Crews and Peoples 2004; Jensen et al. 2012). The dynamics regulating the release of plant-available N from legume residues are however complex and grain yields can be limited by any asynchrony between N supplied by the legume residues and crop N uptake (Crews and Peoples 2004).

Research to date has primarily focused on the efficacy of various N management strategies on different soils under temperate climatic conditions or, in tropical and subtropical climates, on the correction of the main constraints of Oxisols (soil acidity, available phosphorus and soil organic matter). As a result, very little data on efficient N fertilisation strategies are currently available for subtropical cereal cropping systems on Oxisols.

In this study a multi-season ^{15}N tracer recovery experiment was conducted on a subtropical Oxisol to assess the agronomical and environmental performances of applying urea coated with nitrification inhibitors or introducing a legume phase in a cereal-based cropping system. The first investigation of the study focused on the N recovery efficiency of urea coated with a nitrification inhibitor and was performed on a crop rotation composed of wheat followed by maize. The second investigation assessed the fate of ^{15}N-labelled urea in sorghum following a legume ley pasture and compared it to the same crop in rotation with a grass ley pasture.

The overall aims of this study were to: i) compare the N recoveries of different N fertilisation strategies on subtropical Oxisols, including the use of conventional urea or urea coated with a nitrification inhibitor and the presence or absence of legumes in the crop rotation; ii) determine the main pathways of N losses that limit N recovery in these agroecosystems and iii) evaluate the agronomic and environmental sustainability of the N supply practices examined. The results will contribute to define agronomically viable and environmentally sustainable N fertilisation strategies to support future intensification of cereal production on Oxisols.

Materials and Methods

Study site

The study was conducted at the J. Bjelke Petersen Research Station of the Department of Agriculture, Fisheries and Forestry (DAFF). The research site is located in Taabinga (26°34’54,3’’ Latitude South, 151°49’43.3’’ Longitude East, altitude 441 m a.s.l), near Kingaroy, in the southern inland Burnett region of southeast Queensland, Australia. The climate is classified as subtropical, with warm, humid summers and mild, dry winters. Daily mean maximum and minimum temperatures are 20.1°C and 4.0°C in winter and 29.6°C and 16.5°C in summer, respectively. Mean annual precipitation is 776.2 mm and varies from a minimum of 28.6 mm in August to a maximum of 114.1 mm in January (Australian Bureau of Meteorology). The soil is classified as a Tropeptic Eutrustox Oxisol (USDA Soil Taxonomy, USDA (1998)) or as a Orthic Ferrasol (FAO Soil Taxonomy, FAO (1998)) and has a moderately slow permeability. The soil profile is relatively homogenous, characterised by a high clay content (50-65% clay), an effective rooting zone of 1.2 m and a water holding capacity of 100 mm. Physical and chemical soil properties are listed in Table 1.

First investigation (nitrification inhibitor trial)

The first investigation consisted of two cropping seasons: wheat (winter 2011) and maize (summer 2011/2012). Wheat (*Triticum aestivum* L., cultivar Hartog) was planted 6 July after the harvest of a summer mungbean (*Vigna mungo* L.) crop and subsequently harvested 29 November 2011, while maize (*Zea mays* L., cultivar 32P55) was planted 21 December 2011 and harvested 20 June 2012. Two treatments were tested:

- Conventional fertiliser (CONV): fertiliser N applied at rates of 80 and 160 kg N ha^{-1} to wheat and maize, respectively. Rates were designed to achieve maximum yield potential.

- Fertiliser coated with DMPP nitrification inhibitor (DMPP): fertiliser N applied at same rates of CONV treatment. DMPP (3,4-dimethylpyrazole phosphate) was chosen amongst other nitrification inhibitors for the high efficiency in slowing nitrification and reducing N losses (Liu et al. 2013; Weiske et al. 2001a; Weiske et al. 2001b).

During the wheat season both treatments were base dressed with 20 kg N ha^{-1} as diammonium phosphate (DAP - banded at panting) and top dressed at booting stage (Satorre and Slafer 1999) broadcasting 60 kg N ha^{-1} as conventional urea (CONV) or urea coated with the DMPP nitrification inhibitor (DMPP). In maize the two treatments were base dressed at planting by banding 40 kg N ha^{-1} as monoammonium phosphate (MAP) and side dressed at V10 physiological stage -beginning of tenth leaf, (Nanda 2013)- with 120 kg N ha^{-1} as conventional urea (CONV) or with DMPP urea (DMPP). Given the high cost of DMPP, in each season DMPP urea was used only at top/side dressing, when 75% of seasonal N was applied to the crop. During the early stages of crop development irrigation was applied at a rate of 10 mm h^{-1} when water filled pore space (WFPS) values approached 40%. This method avoided water stress limiting the potential yields and prevented fertiliser N to be leached outside the rooting zone. The trial was irrigated on four and two occasions over the wheat and maize seasons, respectively. Timings and amounts of fertiliser application are reported in Table 2, while further information on the study site and crop management can be found in De Antoni Migliorati et al. (2014).

The trial layout was a randomized complete block design with three replicates per treatment. For each treatment, three randomly placed 1 m^2 micro-plots were delimited by stainless steel frames inserted 15 cm into the ground. All micro-plots were surrounded by a buffer of 1 m along each side of the frame. The micro-plots were repositioned before planting maize to avoid ^{15}N contamination across seasons.

The ^{15}N-labelled fertiliser was only applied at top/side dressing to determine the N recovery of DMPP urea and compare it with conventional urea. Each micro-plot received 10% excess ^{15}N enriched urea, which was dissolved in 1 L of deionised water. The labelled fertiliser was applied uniformly with a dispenser over the entire micro-plot area to replicate top dressing (in wheat) or along the band to replicate banding (in maize). For the DMPP treatment the ^{15}N enriched urea was added with DMPP at a ratio of 6 g DMPP Kg^{-1} urea to replicate the same ratio of commercial DMPP urea (Incitec Pivot Fertilisers, personal communication).

Second investigation (legume N trial)

The second investigation consisted of one cropping season (sorghum, planted 12 December 2012 and harvested 18 June 2013) and took place in a field adjacent to the one used for the first investigation. Plots were planted with sorghum (*Sorghum bicolor* L.) following two distinct cropping histories. One crop rotation (hereafter called legume cropping history) included two years of alfalfa pasture (*Medicago sativa*, L.), one season of maize (summer crop) and one season of sulla ley pasture (*Hedysarum coronarium* L., winter crop) prior to sowing sorghum. The other crop rotation (hereafter called grass cropping history) included two years of a mixed pasture predominantly composed by rhodes grass (*Chloris gayana*, K.*)*, one season of maize (summer crop) and one season of wheat (winter crop). Sulla and wheat were managed as green manure crops. The incorporation of sulla residues (2.3 t dry matter ha^{-1}, 1.57% N) was estimated to return approximately 36 kg N ha^{-1} to the soil, while wheat residues (1.24 t dry matter ha^{-1}, 0.75% N) about 9 kg N ha^{-1}. During the sorghum season two treatments were assessed:

- Sorghum grown in the grass cropping history, with 100 kg N ha^{-1} applied (G100). The fertiliser N rate was designed to achieve maximum yield potential.
- Sorghum grown in the legume cropping history, with 70 kg N ha^{-1} applied (L70);

The two treatments were base dressed with 20 kg N ha^{-1} as urea banded at planting, and side dressed at the eight leaf stage (Blum 2004) banding 50 kg N ha^{-1} (L70) or 80 kg N ha^{-1} (G100) as urea (Table 2). The synthetic N rate used in L70 was reduced compared to G100 to account for the expected increase in plant available N arising from the legume inputs. As in the first investigation, irrigation was applied during the early stages of crop development at a rate of 10 mm h^{-1} when WFPS values approached 40%. All plots were irrigated three times over the cropping season; see De Antoni Migliorati et al. (in print) and Bell et al. (2012) for further details on the experiment and the management of the two crop rotations.

The experiment was established in a split plot design with two main plots (legume and grass ley pastures). Lateral movement of N was considered negligible since urea was banded both at side and base dressing. During this investigation micro-plots (1.35 m^2) were therefore sited in the main plots without stainless steel frames. To account for ^{15}N uptake by adjacent plants, micro-plots (0.9 m wide) included one crop row fertilised with ^{15}N enriched urea (1.5 m) and two unfertilised crop rows (1 m) located on either side of the row receiving the ^{15}N-enriched fertiliser. A buffer area of 0.25 m was established at either end of the fertilised crop row. The 5% excess ^{15}N enriched urea was dissolved in 1 L of deionised water and applied in single bands in each micro-plot during both application events.

Samples collection, preparation and analysis

At the beginning of each cropping season soil samples were collected prior to planting to establish soil ^{15}N background levels. At the end of each cropping season plant and soil samples were taken at crop harvest. In wheat and maize all above ground material in the micro-plots was cut near the soil surface using hand clippers. In both seasons the extremely dry conditions of the soil prevented the collection of representative samples of root material. Soil moisture at the end of the sorghum season was higher and plants could be dug out of the ground to collect root material. Sorghum plants from the fertilised and unfertilised rows were collected with hand clippers and stored separately.

Soil sampling was conducted using a core sampler (10 cm diameter) and different strategies were adopted in each season in consideration of fertiliser position. In wheat, where ^{15}N-labelled fertiliser was evenly applied, six cores were randomly taken inside each micro-plot. In maize two transects of three cores each were performed across the inter-row space of each micro-plot, with one core per transect placed over the fertiliser band. In both seasons soil samples were collected at six depths (0-10, 10-20, 20-30, 30-40, 40-50, 50-60 cm). Moist soil conditions at the end of sorghum season enabled a deeper penetration of the core sampler and samples were collected at six depths to a depth of 1 m (0-10, 10-20, 20-30, 30-50, 50-70, 70-100 cm). Two transects of three cores each were performed in the inter-row space between the fertilised and unfertilised rows of each micro-plot, with one core per transect placed over the fertiliser band. At the end of each season reference biomass and soil samples were collected outside the micro-plots as controls for background ^{15}N abundance.

Plant material was mechanically mulched and oven-dried at 60°C to constant weight. Grain, stem and roots (in sorghum) were ground in a planetary cylinder mill and analysed separately. Soil samples were oven-dried at 60°C and ground using the planetary cylinder mill. Soil and plant samples were processed in ascending order of fertiliser rate and all equipment washed with ethanol between treatments to prevent possible cross contamination. The ^{15}N analysis was performed using a 20-22 Isotope Ratio Mass Spectrometer (Sercon Limited, UK).

Ancillary measurements

In addition to soil sampling for ^{15}N analysis, routine soil sampling was conducted at regular intervals to assess soil N dynamics during the growing seasons. Soil samples were taken at three depths (0-10, 10-20, 20-30 cm) and analysed for NH_4-N and NO_3-N. Each soil sample consisted of three subsamples taken at 10 cm intervals from the crop row of then mixed in order to ensure it represented the banded and non-banded areas of the plot. Soil NH_4-N and NO_3-N were extracted by shaking 20 g soil in 100 mL 1 M KC1 solution at room temperature for 60 minutes (Carter and Gregorich 2007). The solution was then filtered and stored in a freezer until analysed colorimetrically for NH_4-N and NO_3-N using an AQ2+ discrete analyser (SEAL Analytical WI, USA).

N_2O fluxes and soil mineral N content were also measured throughout the investigations as part of a comprehensive project assessing N dynamics in cereal-based cropping systems on Oxisols. N_2O emissions from each treatment were measured every three hours using a chamber-based automated greenhouse gas measuring system installed next to the micro-plots. For more information about N_2O-N losses during the two investigation see De Antoni Migliorati et al. (2014) and De Antoni Migliorati et al. (in print).

Four frequency domain reflectometers (FDR, EnviroScan probes, Sentek Sensor Technologies, Australia) were installed at the field site to continuously monitor the water content at three depths (0-10 cm, 10-20 cm, 20-30 cm). Soil temperature was measured every 5 minutes with resistance temperature detectors (RTD, Temperature Controls Pty Ltd, Australia) buried at 10 cm, 20 cm and 30 cm in the proximities of chambers. Rainfall data were obtained from a weather station located at the study site.

Calculations and statistical analysis

All calculations were conducted on oven-dried basis. Total recovery of applied ^{15}N-labelled fertiliser was determined by mass balance. The percentage of N derived from the labelled fertiliser (Ndff) in each plant and soil pool was determined using the following formula (IAEA 2001):

$$Ndff = \frac{(atom\%\ ^{15}N\ \ _{sample} - atom\%\ ^{15}N\ \ _{control})}{(atom\%\ ^{15}N\ \ _{labelled\ fertiliser} - atom\%\ ^{15}N\ \ _{unlabelled\ fertiliser})} \times 100$$

Equation 1

The percentage of ^{15}N recovered in each pool was calculated as

$$^{15}N\ recovery = \frac{^{15}N\ recovered\ (kg\ N\ ha^{-1})}{^{15}N\ applied\ (kg\ N\ ha^{-1})} \times\ 100$$

Equation 2

Fertiliser N recovery in the root biomass of wheat and maize was calculated assuming a N recovery similar to the one in straw and stalks, respectively (Anderson 1988). Root biomass was estimated using a root : shoot ratio of 0.31 for wheat (Manschadi et al. 2008; Siddique et al. 1990) and 0.22 for maize (Anderson 1988; Demotes-Mainard and Pellerin 1992).

Statistical analyses were performed within the SPSS 22 environment (IBM Corporation, USA). Differences in ^{15}N recoveries of different pools were assessed with the ANOVA test using a confidence interval of 95%.

Results

First investigation

Throughout the first investigation the field trial received a total of 919 mm rainfall, the majority of which occurred during the summer season (520 mm) (Fig. 1). Soil mineral N content was relatively high at planting of wheat and gradually decreased during the two cropping seasons. Substantial increases in soil N were observed in both seasons after top/side dressing (Fig. 2). Soil conditions were considerably warmer and wetter during the maize season, especially at the time of side dressing.

In both seasons the use of DMPP urea did not significantly affect N recovery, grain yield and biomass production (Fig. 3). Plant recovery of ^{15}N-labelled fertiliser was higher in wheat (CONV: 72.9%, DMPP: 76.2%) than in maize (CONV: 49.7%, DMPP: 50.9%) (Table 3). The residual ^{15}N-labelled fertiliser recovered in the soil ranged from 25.8% (CONV) to 23% (DMPP) in wheat and from 35.9% (CONV) to 32.6% (DMPP) in maize. Whilst at the end of the wheat season almost all residual ^{15}N-labelled was confined to the upper 10 cm, a higher amount of N moved throughout the soil profile in maize (Fig. 4).

In wheat about 33.8% (CONV) and 35.7% (DMPP) of plant N derived from the fertiliser N applied at top dressing, while in maize Ndff values varied between 51.9 (CONV) and 50.9 (DMPP). In both crops fertiliser N was primarily recovered in grains and secondarily in the straw/stalks and root components. The estimated proportion of ^{15}N recovered in roots was consistent with results reported by Kumar and Goh (2002) and Ichir et al. (2003) for wheat and by Mahmood et al. (2011) and Vanlauwe et al. (2001) for maize.

N_2O-N losses measured after top dressing in wheat amounted to 0.2% of the fertiliser N applied at top dressing, while in maize they varied between 1.3% (CONV) and 0.3% (DMPP) of the N banded at side dressing (Table 3). Accounting for these gaseous losses, the amount of applied ^{15}N-labelled fertiliser that was not recovered in the plant-soil system during the wheat season ranged from 1.1% (CONV) to 0.1% (DMPP). During the maize seasons this percentage varied between 13.2% and 16.2% in the CONV and DMPP treatments, respectively (Table 3).

Second investigation

Over the study period a total of 827 mm of rain fell at the study site, including one heavy rainfall event of 234 mm during a thunderstorm on 27 January 2013. Over 70% of the total rainfall was concentrated between 25 January and 3 March (Fig. 1). A gradual decrease in soil mineral N was observed in both treatments during the growing season. No consistent response to history or fertiliser application could be measured in terms of soil mineral N (Fig. 2). Similarly to the maize season, average soil temperatures ranged from a maximum of 29.7°C (December 2012) to a minimum of 11.9°C (May 2013).

Sorghum production was substantially affected by cropping history. Despite a 30% reduction in the amount of N fertiliser applied, the production of grain and biomass in L70 was comparable to that in G100 (Table 3). This was reflected in the percentage of plant N derived from fertiliser: in L70 only 26.3% of plant N originated from the fertiliser, while in G70 the percentage was 44.9%. The recovery of applied N fertiliser in L70 (70.9 ± 2.1) was significantly greater than in G100 (52.8 ± 6.1) (Fig. 3). In both treatments fertiliser N was mostly recovered in the grains, with lesser quantities in stalks and roots.

The amount of ^{15}N-labelled fertiliser left in the soil in the G100 treatment (43.3 ± 4.4 %) was significantly higher than in G70 (27.3 ± 2.8) and was mainly concentrated in the top 10 cm of soil profile (Fig. 4). After taking into consideration the N_2O-N losses, the amount of fertiliser N that could not be accounted for ranged between 0.9 (L70) and 2.6% (G100). In both investigations unaccounted ^{15}N was assumed to be lost from the monitored crop-soil system via deep leaching or through the nitrification/denitrification processes. Losses via runoff and NH_3 volatilisation were considered negligible since in both investigations ^{15}N-labelled urea was applied as a liquid solution in a sub-surface band.

Discussion

Fertiliser as source of crop N

As expected, the amount of plant N derived from labelled fertiliser varied widely across crops and investigations. In the first investigation, the average percentage of crop N derived from ^{15}N-labelled fertiliser was 34.7 ± 1.3 in wheat and 52.4 ± 0.7 in maize. The low reliance of wheat on N fertiliser can be attributed to the cropping history of the field trial, as the site had previously been cropped with mungbean. This crop was harvested six weeks before planting wheat and mungbean residues were incorporated in the soil at a rate of approximately 1.8 t DM ha^{-1}. As confirmed by the high soil N levels measured at wheat planting, the mineralisation of mungbean residues supplied a substantial amount of N to the wheat plants, reducing the dependence of wheat on the synthetic N source. Similar results were reported by Dourado-Neto et al. (2010) for wheat in rotation with peanut cropped on an Entisol under tropical conditions.

Synthetic fertiliser represented a more important source of N in the maize season and two factors may have contributed to this. Firstly, maize was side dressed with twice the amount of N when compared to wheat and therefore maize plants had a greater pool of readily available mineral N in the soil profile (Fig. 2, Fig. 4). Moreover, maize was planted three weeks after wheat harvest and native soil N was lower than at the beginning of the wheat season (Fig. 2). Continuous cereal cropping has been reported to increase the crop reliance on synthetic fertiliser N (Tilman et al. 2002) and significantly lower Ndff levels (25.3-40.8%) were reported by Blesh and Drinkwater (2014) for fertilised maize (150 kg N ha^{-1}) in rotation with soybean.

A similar response to cropping history was observed during the second investigation. Despite yields and biomass production in L70 and G100 being comparable, a significantly higher reliance on fertiliser N was observed in sorghum plants in G100 (44.9% ± 5) compared to that in L70 (26.3% ± 5.1). Sorghum was planted two weeks after the incorporation of the pasture residues. Typically, the highest N mineralisation rates from legume residues occur about six weeks from the termination of the pasture (Fox et al. 1990; Park et al. 2010). In the present study this would have coincided with the moment of maximum N uptake of sorghum (week four - eight leaf stage), although it was not possible to determine whether the extra 25 kg N ha^{-1} available to the sorghum crop in L70 was derived from the recent small input of sulla biomass, the previous alfalfa ley phase or, more likely, a combination of both. As in the maize experiment, the greater reliance on fertiliser as a source of N in G100 was consistent with the small amount of N provided by the decomposition of grass/wheat residues and the high fertiliser N rate applied. No direct comparisons with other studies could be made for sorghum as, to the knowledge of the authors, no studies have been published on crop N derived from fertiliser for this crop under similar conditions.

Collectively, these results illustrate the implications of including legumes in cropping systems conducted on Oxisols. While Oxisols can contain large amounts of organic matter and N under native vegetation, these reserves generally decline rapidly under cultivation (Bell et al. 1995). Consequently, cropped Oxisols are typically characterised by low levels of soil organic matter and native N, meaning low inherent fertility and little resilience when used for intensive cropping (Mulongoy and Kang 1986; Vieira et al. 2010). Continuous cereal cropping in these agroecosystems has the potential to rapidly erode native soil N supply and lead to a greater reliance on fertiliser N to meet crop demand (Dalal and Mayer 1986; Tilman et al. 2002). Conversely, the presence of a legume phase in a cropping system has been shown to have the potential to increase the soil organic matter and organic N content (Giller and Cadisch 1995; Rochester et al. 2001), substantially reducing therefore the reliance of subsequent crops on synthetic fertiliser N.

Crop N recoveries and N losses

Crop recoveries of ^{15}N fertiliser measured in the two investigations were at the higher end of values reported for grain cropping systems conducted under tropical or subtropical climatic conditions (Dourado-Neto et al. 2010; Mubarak et al. 2003; Pilbeam 1995; Ssali 1990; Xu et al. 1992). As emphasised by Dourado-Neto et al. (2010), N recoveries of annual crops are highly variable and are influenced by multiple factors. Amongst these, the most prominent are the synchronisation between fertiliser N release and plant N uptake, the availability of native soil N and the occurrence of environmental conditions that can stimulate N losses.

Effective synchronisation between crop N demand and fertiliser N supplied is likely to have been achieved during both investigations. Wheat and maize were top/side dressed at a stage when soil N reserves had been depleted during the early stages of crop growth (Fig. 2), enabling a fast recovery of applied fertiliser ^{15}N. In sorghum the ^{15}N-labelled fertiliser was split between at-planting and in-season applications, with differing N rates reflecting differences in the soil N supply. The results of this study showed that crop recoveries of applied ^{15}N varied substantially across seasons and were influenced by environmental conditions and amounts of N applied. Significantly higher crop recoveries (≥70%) were observed in both treatments in wheat and in the L70 treatment in sorghum, where ^{15}N-labelled fertiliser rates were 60 and 70 kg N ha^{-1}, respectively. Conversely, ^{15}N recoveries did not exceed 53% in maize and in the G100 treatment in sorghum, where ^{15}N-labelled fertiliser rates were 120 and 100 kg N ha^{-1} (Fig. 3).

In winter (wheat season) the environmental conditions were not conducive for excessive N losses. As indicated by the low N_2O-N losses, the nitrification and denitrification processes are likely to have been inhibited by the relatively low soil temperatures (constantly below 20°C). Moreover, the low amount of rainfall that occurred in the month following top dressing (154 mm) would not have triggered denitrification or caused important leaching events in this soil type. Accordingly, the vast majority of labelled fertiliser N not recovered in the crop was found in the top 10 cm of the soil profile (Table 3) and unaccounted N was limited to 1% of applied ^{15}N.

In summer, conditions at side dressing were more favourable for stimulating N losses (Fig. 1). In both maize and sorghum seasons the high soil moisture conditions occurring concurrently with elevated soil temperatures would have stimulated the activity of nitrifying and denitrifying bacteria. Moreover, significant rainfall events occurred a few days after side dressing, resulting in higher amounts of ^{15}N leached down the soil profile (Fig. 4) compared to the winter season.

Despite soil conditions were conducive for high N losses, the amount of unaccounted ^{15}N in the maize and sorghum seasons was relatively low compared to other studies conducted on summer crops grown on soils other than Oxisols (Blesh and Drinkwater 2014; Dourado-Neto et al. 2010; Sanchez and Blackmer 1988; Smil 1999; Zhang et al. 2010). The low N losses measured in this study can be explained considering the physical and chemical characteristics of the soil.

The permeability of the soil was sufficient to avoid prolonged periods of saturation of the soil profile even after the high summer rainfall events, while the relatively low content of soil organic C would have resulted in a limited supply of labile C to support denitrification. As indicated by the relatively low N_2O emissions measured in the two summer crops (Table 3), denitrification could therefore not go to completion and only moderate quantities of N_2 are likely to have been lost after significant rain events.

On the other hand, the high clay content of the soil reduced the water infiltration rates even during the intense rain events occurred during the two summer seasons (Fig. 1). The moderate soil permeability limited NO_3^- leaching and maintained the majority of the N in the rooting zone, enabling in this way a wider window of opportunity for the plants to adsorb the

N supplied with fertilisation. As a result, the unaccounted fertiliser N during the summer cropping seasons was limited to amounts varying between 0.9% (L70) and 16.2% (DMPP) of applied N fertiliser.

In this study N losses via runoff and NH_3 volatilisation were minimised by the fertiliser application method, while NO_x–N losses were considered negligible. Nitric oxide in soil is a by-product of the nitrification and denitrification processes, and several laboratory study have reported NO:N_2O emissions ratios varying from 0.01 to 1 (Skiba et al. 1997). Consequently, fertilizer-induced NO emissions were estimated to range from 0.3% to 1.4% of the applied N, a value in close agreement with those suggested by Skiba et al. (1997) and Veldkamp and Keller (1997), and similar to that measured by Fernandes Cruvinel et al. (2011) in a fertilised Oxisols cropped with maize.

During the summer cropping seasons the majority of the unaccounted fertiliser N is likely to have been lost in the deeper layers of the soil profile via leeching. In maize, when the amounts of unaccounted fertiliser N were highest (13.2% and 16.2%), approximately 11% of fertiliser N was recovered in the monitored subsoil (30 - 60cm). This aspect indicates a net N movement towards the lower soil layers and suggests that a further 10% of fertiliser N could have been lost in the unmonitored strata of the soil profile, i.e. deeper than 60 cm.

DMPP was not effective in increasing crop N recovery, although values tended to be slightly higher than in the CONV treatment (Table 3). Several studies have reported that nitrification inhibitors have the potential to significantly increase N recoveries only when relatively large amounts of fertiliser N are lost via leaching or denitrification (Abalos et al. 2014; Chaves et al. 2006; Freney et al. 1993; Walters and Malzer 1990; Wolt 2004). The intrinsic characteristics of the Oxisol monitored in this study limited the possibility of DMPP to significantly improve the fertiliser N use efficiency since relatively low N losses were observed also when conventional urea was applied.

In fact, also in the CONV treatment the majority of the fertiliser N that was not taken by the crop remained confined in the top soil. The high clay content of the Oxisols limited the vertical movement of fertiliser N in the soil and the percentage of soil ^{15}N recovered in the top 10 cm at the end of the wheat and maize seasons amounted to 84 and 50% of the total ^{15}N recovered in the soil profile, respectively (Fig. 4). Similar results were observed in the second investigation, when after fertilising sorghum with conventional urea the ^{15}N recovered from the first 10 cm constituted 76% (L70) and 88% (G100) of the total ^{15}N recovered in the soil.

Implications

Overall, fertiliser N rates were the main factor limiting N recovery in the crops. Highest fertiliser N recoveries were observed in the CONV and DMPP treatments in wheat (>70%) and in the L70 treatment in sorghum (70%), which were fertilised with 60 and 70 kg ^{15}N ha^{-1}, respectively. The low N rates applied in these treatments enabled to synchronise the fertiliser N supply with plant N demand. Fertiliser N was therefore used more efficiently by the crop and less (approximately 25%) was left in the soil.

In contrast, significantly lower fertiliser N recoveries were measured in the CONV and DMPP treatments in maize (approximately 50%) and in the G100 treatment in sorghum (53%), which received 120 and 100 kg ^{15}N ha^{-1}, respectively. The amounts of ^{15}N recovered in the soil of these three treatments were remarkably similar (39.1 - 43.3 kg N ha^{-1}), while the quantities of leached or otherwise unaccounted ^{15}N were greater in the CONV and DMPP treatments in maize, where the rate of labelled N applied at side dressing (120 kg N ha^{-1}) was substantially higher than in G100 (80 kg N ha^{-1}).

The introduction of a legume phase in the cereal-based cropping system proved to be the most effective N strategy under both the agronomical and environmental perspectives. The mineralisation of the legume residues provided a substantial N supply to the following cereal crops and reduced the cereal reliance on synthetic fertiliser compared to cereals planted after a non-leguminous crop. The decreased reliance on synthetic N inputs allowed for reducing fertiliser N rates to the levels necessary to reach maximum yield potential. In particular, this strategy enabled lowering the amount of fertiliser N side dressed to the summer cereal crop, the occasion when the highest quantities of annual synthetic N are applied. Build-up of high amounts of NO_3^- in the soil following fertilisation was therefore limited and N_2O losses were caused mainly by temporary increases of NO_3^- levels due to fertiliser application. Consequently, cumulative N_2O emissions were primarily a function of the N fertiliser rate applied, while cropping history had no significant effect.

Conclusions

Collectively, the results of this study point to limiting the application rates of synthetic fertiliser N as the most effective strategy to reduce N losses and increase fertiliser N recovery in subtropical Oxisols. Future N management strategies in these agroecosystems should therefore focus on the introduction of legumes to reduce the reliance of cereal crops on synthetic N fertilisers and minimize the agronomic inefficiencies due to fertiliser N losses. A critical aspect for the success of these N management strategies will be to achieve a good synchrony between the N released from the degradation of legume residues and the N uptake of the subsequent crop.

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Table 1 Main soil physical and chemical properties (0-30 cm) of the experimental site at Kingaroy research station, Queensland, Australia

	First investigation	Second investigation	
Soil Property (0-30 cm)	-	**Legume ***	**Grass ***
pH (H_2O)	5.58	5.12	5.3
SOC (Mg C ha^{-1})	53.27	62.69	66.87
DOC (kg C ha^{-1})	39.56	43.04	56.05
Bulk density 0-30 cm (g cm^{-3})	1.33	1.18	1.18
Texture (USDA)	Clay	Clay	Clay
Clay (%)	55	55	55
Silt (%)	14	14	14
Sand (%)	31	31	31

* Cropping history

Table 2 Times of application and N rates of labelled and unlabelled fertilisers during the two investigations at Kingaroy research station, Queensland, Australia

Crop	Time of fertiliser application	Fertilization [kg-N ha^{-1}]	
		CONV	**DMPP**
Wheat	Planting	20 (DAP[†])	20 (DAP[†])
	Top Dressing (broadcasted)	60 (urea) **	60 (DMPP urea) **
Maize	Planting	40 (MAP[††])	40 (MAP[††])
	Side Dressing (banded)	120 (urea)**	120 (DMPP urea)**
		L70	**L100**
Sorghum	Planting	20 (urea) *	20 (urea) *
	Side Dressing (banded)	50 (urea) *	80 (urea) *

[†] Diammonium phosphate
[††] Monoammonium phosphate
** Fertiliser labelled with 10% ^{15}N urea
* Fertiliser labelled with 5% ^{15}N urea

Table 3 Dry matter, plant N derived from ^{15}N-labelled fertiliser (Ndff) and recovery of added ^{15}N measured at the end of the two investigations (mean ± SD, n=3). Statistically significant differences are denoted

Crop	**Pool**	**DM [t ha^{-1}]**		**Ndff [%]**		**^{15}N recovered [%]**	
		CONV	**DMPP**	**CONV**	**DMPP**	**CONV**	**DMPP**
Wheat	Grain	3.5 ± 0.5	3.6 ±0.8	24.8 ± 2.7	26.0 ± 2.4	53.3 ± 2.2	55.6 ± 7.5
	Straw	7.7 ± 1.3	7.8 ±1.3	6.9 ± 0.9	7.4 ± 0.7	14.9 ± .2.2	16.1 ± 3.5
	Roots ‡	2.4 ± 0.4	2.4 ±0.4	2.1 ± 0.1	2.3 ± 0.2	4.7 ± 0.8	5.0 ± 0.8
	Plant total	13.6 ± 2.2	13.9 ±2.5	33.8 ± 2.9	35.7 ± 2.4	72.9 ± 3.3	76.7 ± 11.3
	Soil					25.8 ± 6.4	23.0 ± 5.3
	N_2O after top dressing					0.2 ± 0.02	0.2 ± 0.01
	N accounted for ^{15}N					98.9 ± 5.8	99.9 ± 8.8
	N unaccounted for ^{15}N					1.1	0.1
Maize	Grain	8.2 ± 1.3	7.7 ± 0.3	42.2 ± 3.4	42.0 ±4.8	40.3 ± 6.7	40.3 ± 0.7
	Stalks	4.7 ± 1.2	4.9 ± 0.7	8.0 ± 0.5	8.9 ±0.9	7.6 ± 1.4	8.6 ± 0.6
	Roots ‡	1.0 ± 0.3	1.1 ± 0.2	1.8 ± 0.04	2.0 ±0.1	1.7 ± 0.4	2.0 ± 0.3
	Plant total	13.9 ± 2.7	13.7 ± 1.0	51.9 ± 3.8	52.9 ±5.4	49.7 ± 8.6	50.9 ± 0.6
	Soil					35.9 ± 5.7	32.6 ± 9.3
	N_2O after side dressing					1.3 ± 0.6	0.3 ± 0.2
	N accounted for ^{15}N					86.8 ± 12.1	83.8 ± 9.6
	N unaccounted for ^{15}N					13.2	16.2
		L70	**G100**	**L70 †**	**G100 †**	**L70 †**	**G100 †**
Sorghum	Grain	8.9 ± 1.5	7.0 ± 0.8	17.1 ± 4.5	27.7 ± 4.0 *	45.6 ± 4.3	32.4 ± 2.2 **
	Stalks	11.9 ± 1.5	9.2 ± 1.8	8.3 ± 1.4	15.4 ± 3.0 *	22.7 ± 5.3	18.2 ± 4.6
	Roots	2.4 ± 0.3	2.0 ± 0.3	1.0 ± 0.2	1.8 ± 0.5	2.6 ± 0.3	2.2 ± 0.7
	Plant total	23.2 ± 3.2	18.1 ± 2.7	26.3 ± 5.1	44.9 ± 5.0 *	70.9 ± 2.1	52.8 ± 6.1 **
	Soil					27.3 ± 2.8	43.3 ± 4.4 **
	N_2O					1.0 ± 0.3	1.4 ± 0.2
	N accounted for ^{15}N					99.1 ± 4.9	97.4 ± 2.6
	N unaccounted for ^{15}N					0.9	2.6

‡ estimated values
† values are inclusive of N recovered by plants in unfertilised row
* $p < 0.05$
** $p < 0.01$

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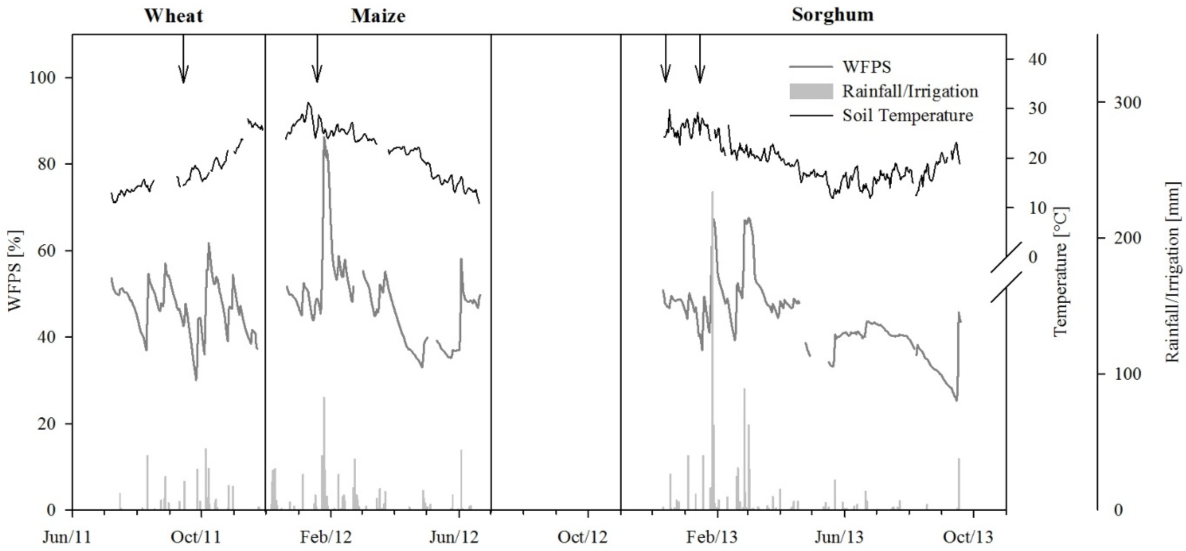

Fig. 1 Water filled pore space (WFPS) measured at 0-30 cm, soil temperature (0-30 cm) and rainfall and irrigation events during the wheat, maize and sorghum seasons at Kingaroy research station, Queensland, Australia. Arrows indicate the time of application of ^{15}N-labelled fertiliser

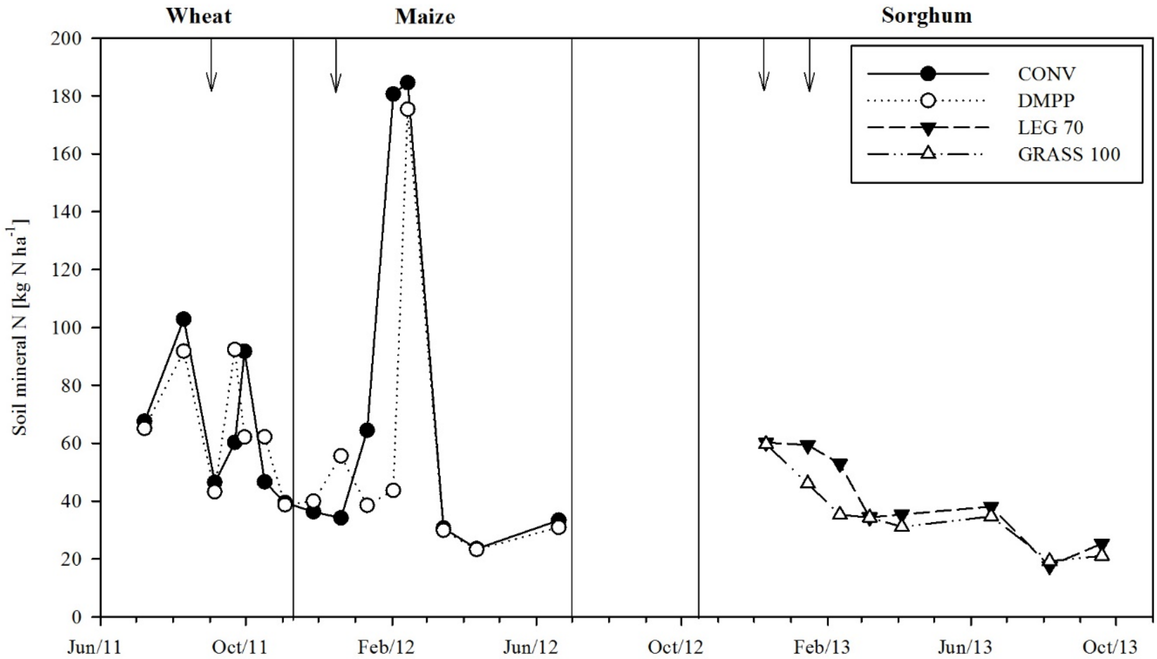

Fig. 2 Soil mineral N levels (NH_4^+ + NO_3^-) in the top 30 cm for the four treatments during the wheat, maize and sorghum seasons at Kingaroy research station. Arrows indicate the time of application of ^{15}N-labelled fertiliser

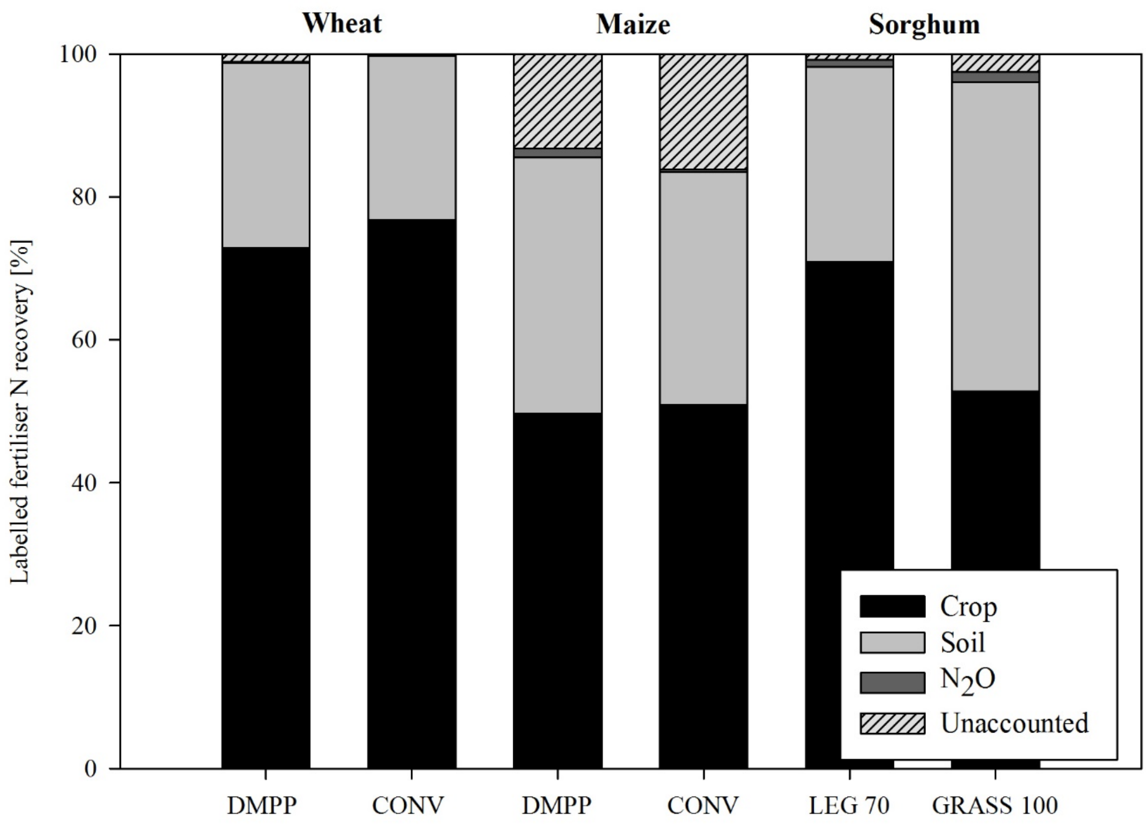

Fig. 3 Mean cumulative crop and soil recoveries and losses of ^{15}N-labelled fertiliser for the four treatments during the wheat, maize and sorghum seasons

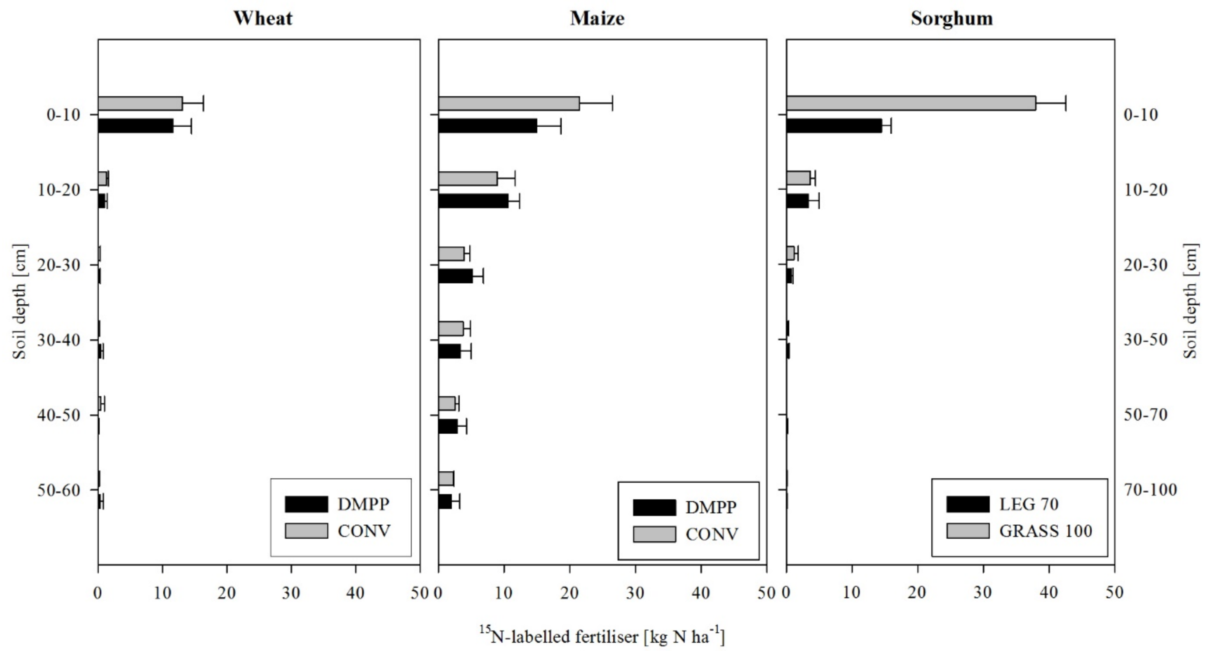

Fig. 4 ^{15}N-labelled fertiliser recovered in the soil by depth increment during the wheat, maize and sorghum seasons. Depth increments in maize were the same of wheat. Error bars indicate the standard errors